Senior Thesis

MODFLOW Model of The Ohio State University, Columbus Campus

By
Calliope A. Voiklis
2000

Submitted as partial fulfillment of
The requirements of the degree of
Bachelor of Science in Geological Sciences
At The Ohio State University,
Spring Quarter, 2000

Approved by:
Frank W. Schwartz

Dr. Franklin W. Schwartz

Table of Contents

List of Figures

Tables

INTRODUCTION

Purpose of the Study

In 1999, The Ohio State University embarked on an ambitious renovation of the football stadium. Among other things, plans called for the field to be lowered about 20 feet, which is below the existing water table and the Olentangy River. Given the permeable setting, it was expected that ground-water inflow would be a major problem. Modifications to the design of the stadium were made to overcome these problems. These modifications included a cut off wall to the bedrock and drains beneath the field itself.

The ground-water problems associated with the stadium renovation provided an ideal opportunity to exercise modeling approaches that were capable of predicting patterns of ground-water flow toward the stadium and likely quantities of inflow. The purpose of this thesis is to describe the patterns of inflow and inflow amounts to the stadium with and without ground-water control features. The approach involved creating a steady- state MODFLOW model of The Ohio State University Campus. This thesis describes the development and application of the model including the methods used in creating a grid, assigning values for constant head and recharge, calibrating the model, and approaches taken to make the model correctly represent the stadium. Given a lack of data, this model exercise is intended to be an illustration of the likely ground-water conditions on The Ohio State Campus, but by no means a perfect simulation.

Area of Interest

Any numerical simulation requires definition of a simulation domain appropriate to the scale of the problem. The specific area of interest in this case extends from the Olentangy River to Summit St. in the West - East direction and Lane Ave. to King Ave. in the North - South direction (Figure 1). This area of 1.4 miles squared is located in Franklin County of Ohio, and within the city of Columbus. The topography of this study area is controlled by the Olentangy River valley, which trends north - south. Along the river is a broad flood plain upon which the football stadium is constructed. The main part of the campus occupies the valley walls and uplands away from the river.

Geology

The main geologic units of interest on Columbus campus include a limestone and shale bedrock, an overlying sand and gravel unit, and finally till. The oldest unit of interest in this study is limestone, undifferentiated Columbus Limestone and Delaware Limestone, which both are Middle Devonian in age. The Columbus Limestone ranges from a limey dolomite to a low-magnesium limestone (Cunningham, et al., 1996). The Delaware Limestone consists of a brown/blue gray limestone and brown shale with chert (Cunningham, et al., 1996). It is likely that this unit sub crops along the Olentangy River and flood plain. Overlying the limestone, along the valley wall and beneath the main campus are the Olentangy Shale and Ohio Shale, which both are Upper Devonian in age. The Olentangy Shale is made up of "blue-black soft shale containing limestone concretions" (Cunningham, et al., 1996). The Ohio Shale is a "black carbonaceous shale and gray siliceous shale" (Cunningham, et al., 1996).

The sand and gravel unit is a glacial drift unit of Pleistocene age. The deposition of this unit is related to Illinoian and Wisconsinan glaciations, which occurred

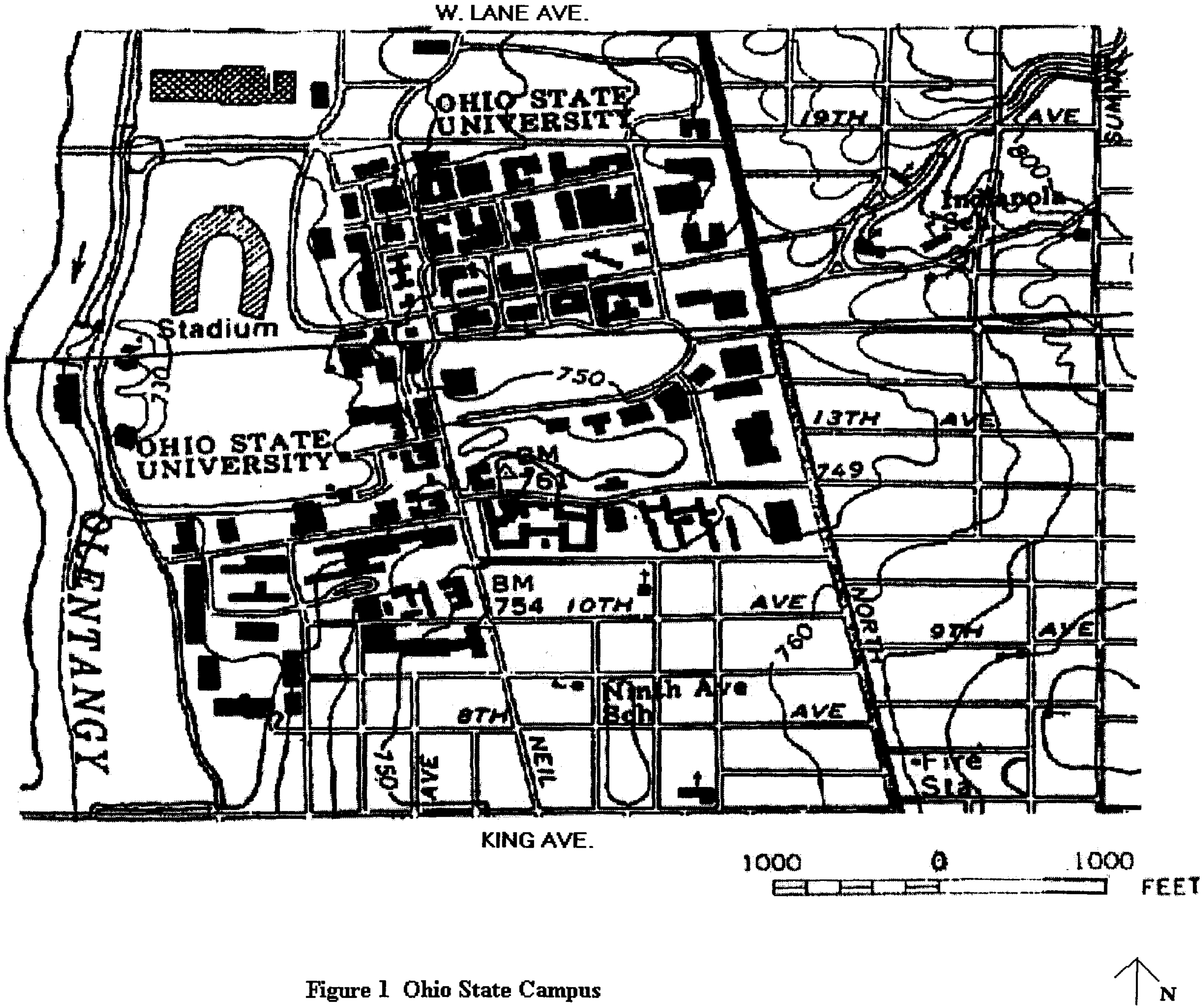

Figure 1 Ohio State Campus

300,000 to 130,00 and 24,000 to 14,000 years ago respectively. This unit represents a sand and gravel outwash related to glacial activity in Ohio (Cunningham, et al., 1996). These older deposits are mantled by clayey to silty glacial till. This till likely formed due to a minor readvance of glaciers during the late Wisconsin.

The University Architect and physical planning office originally provided Borehole Logs for various buildings located on campus. These data were used to create two maps, a depth to bedrock map (Figure 2) and a map showing the thickness of the sand and gravel (Figure 3).

The data compiled from the logs indicate that the elevation of the bedrock surface ranges from 664 to 732 feet above sea level. Contouring these data show that the bedrock is mostly flat at 670 feet above sea level in the middle of the map area. To the southwest the bedrock elevation decreases and to the northeast and southeast, the bedrock elevation increases.

Figure 3 shows that the sand and gravel unit under the campus is 20 to 60 feet thick. The greatest thickness, which is 60 feet, is located at the Sullivan Cancer Hospital. Although this very thick part is limited in extent, there are significant areas in the river valley where the thickness is greater than 40 feet.

Hydrogeology

There are only limited data available concerning the hydrogeologic properties of the three main units on the site. Values of hydraulic conductivity were based on estimates taken from Domenico and Schwartz (1998) and Cunningham and others (1996). The area of interest in the Cunningham and others report is very close to The Ohio State

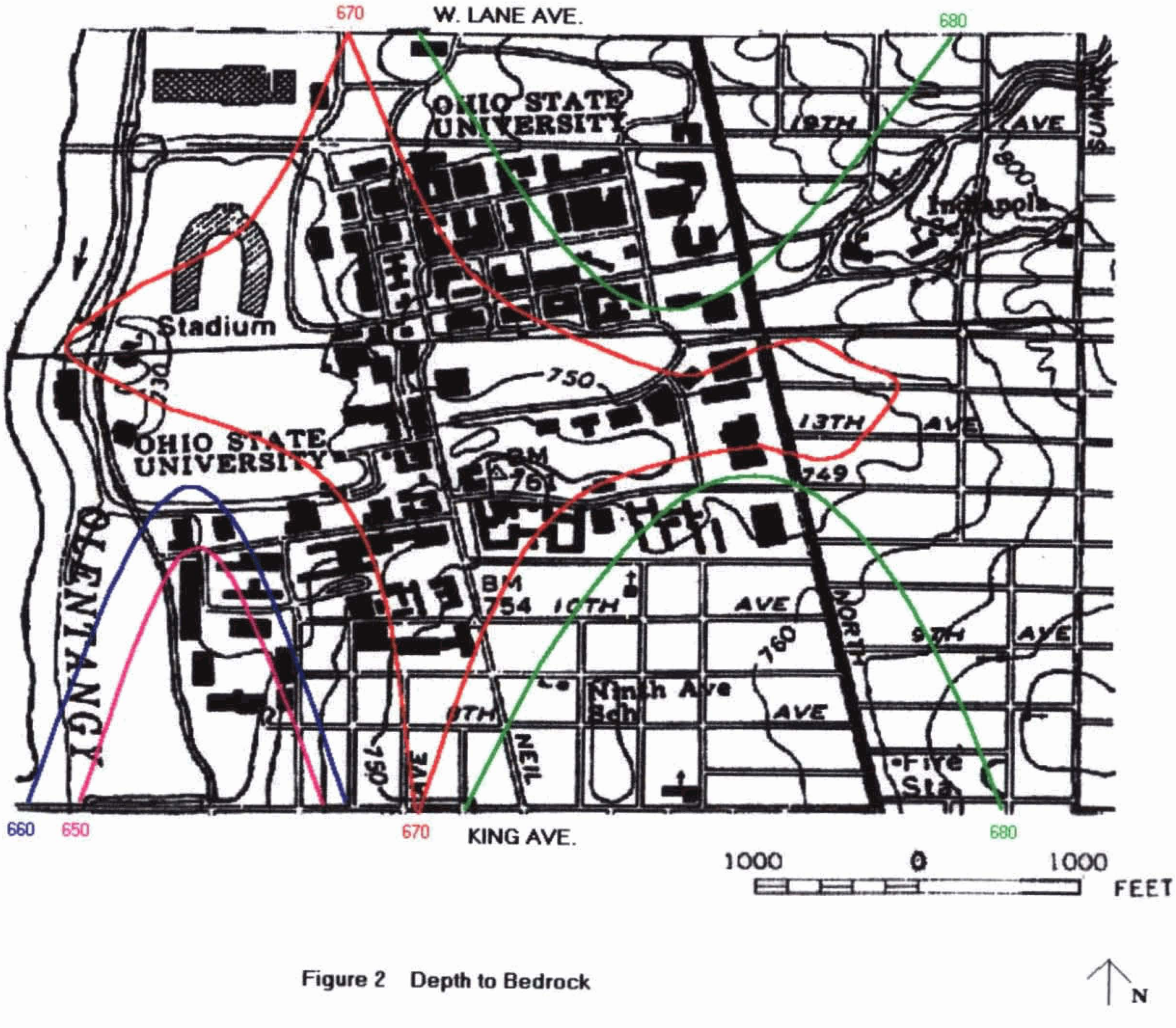

Figure 2 Depth to Bedrock

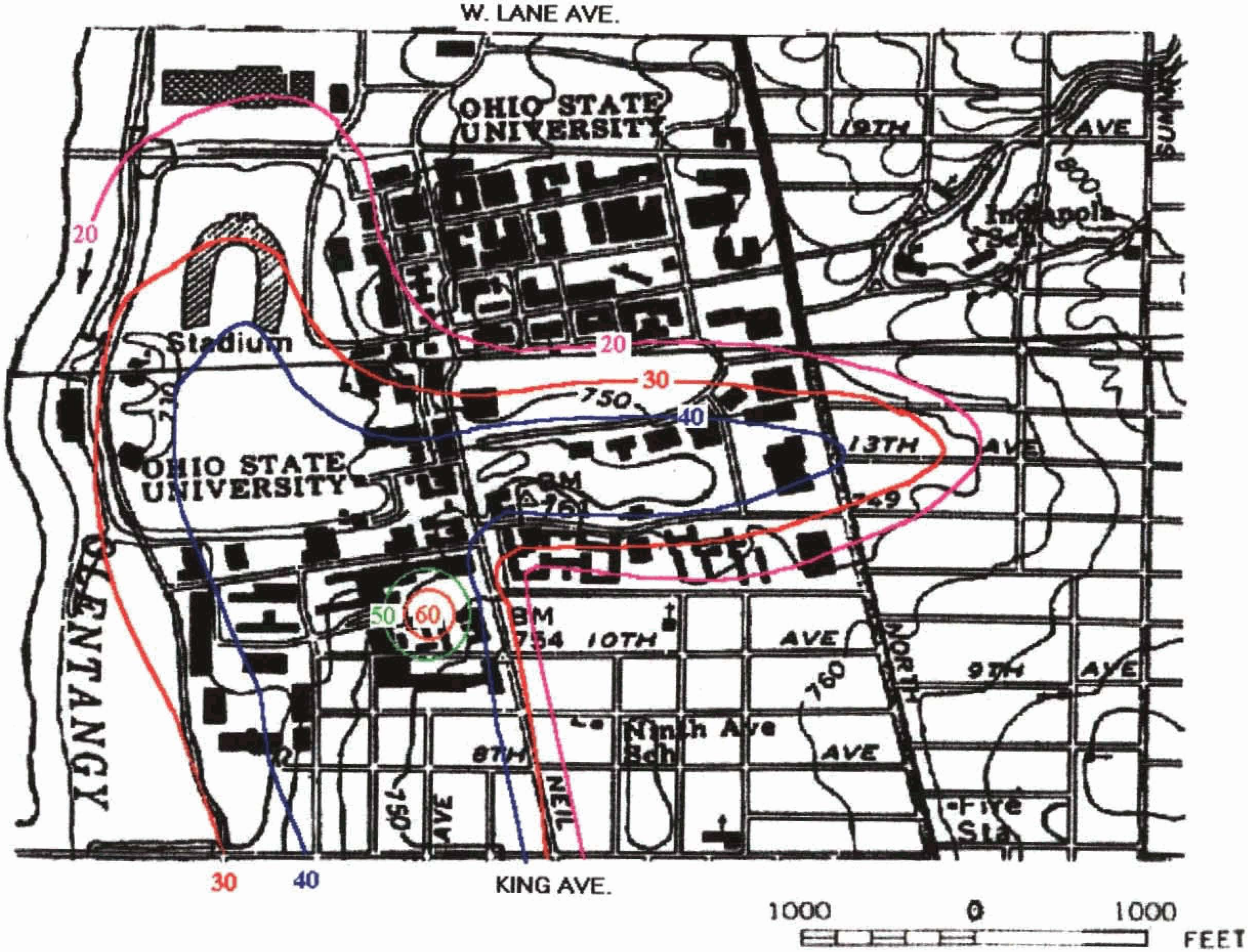

Figure 3 Thickness of Sand and Gravel

University and thus, provides a reasonable estimate of hydraulic conductivity. Both limestone and shale bedrock are weathered and fractured in the upper 10 to 15 feet. This zone was considered as a single hydrostratigraphic unit with a hydraulic conductivity of 10 ft/day. Clearly the thick sand and gravel unit is a major aquifer. The hydraulic conductivity is estimated to be 300 ft/day, based on Cunningham and others (1996). The till has an extremely low hydraulic conductivity compared to the aquifer and bedrock and therefore does not contribute significantly to the ground-water movement of The Ohio State Campus. For this reason the till is not specifically included in the model.

The water table occurs at depths ranging from approximately 10 to 20 feet. It is generally a subdued replica of the topography and rises to the east. This water-table topography generally provides an east to west pattern of flow. A major buried valley from the Ohio Union through Mirror Lake likely produces a local deviation in pattern of flow.

As part of this study, I measured the water-table elevation in the well installed along 12th Ave., immediately south of Mendenhall Laboratory. This measurement indicated a depth to water of 20 feet and an elevation of 745 feet above sea level.

MODFLOW MODEL

Ground-water Models

Ground-water modeling can be a useful tool to predict and interpret ground-water movement. Two main ground-water models are, ground-water flow models and solute transport models. "Ground-water flow models solve for the distribution of head, whereas solute transport models solve for the concentration of solute as affected by advection, dispersion, and chemical reactions, ..." (Anderson et al., 1992). Computer codes are important in ground-water modeling because large numerical problems can be calculated easily and quickly. Three well recognized computer codes are MODFLOW, PLASM, and AQUIFEM-1. MODFLOW and PLASMA are finite difference models, while AQUIFEM-1 is a finite element model. Choosing a code to work with depends on the dynamics of the problem and preference of the user. MODFLOW was used in my study because it would produce appropriate results to the problem, while at the same time is fairly easy to work with.

MODFLOW solves the following governing equation, discussed by Anderson et al., (1992).

$$\frac{\partial}{\partial x}(Kx\,\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(Ky\,\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(Kz\,\frac{\partial h}{\partial z}) = Ss\,\frac{\partial h}{\partial t} - R$$

where Kx, Ky, and Kz are components of the hydraulic conductivity tensor. Ss is specific storage; R is a general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit time (Anderson et al.1992).

Grid

The first step in construction of the MODFLOW model involved subdividing the study area into rows and columns to provide the grid, which consists of 50 row and 50 columns. With square grid blocks, this grid provided cells about 128 feet on a side. The model is designed with two vertical layers, the upper layer representing the confined aquifer unit and the bottom layer representing the carbonate bedrock aquifer. A simplified base map was created using the program Surfer and imported into MODFLOW. This step made it easy to identify how various section of the campus would be represented on the grid (Figure 4).

<u>Top and Bottom Elevations of each layer</u>

Layer 1

On the topographic map, the top elevations range from 730 to 800 feet (Figure 1). The top layer underlying the campus is till and, as noted above, the till layer does not play a significant role in this model so it is ignored. Therefore the top layer is a confined aquifer that has been given a constant top elevation of 730 feet. This constant value was chosen because it is a close midpoint of the aquifer's top elevation. Conveniently this keeps the model simple, while still providing a reasonably realistic representation.

An Excel spreadsheet, divided into 50 rows and columns was used to map the aquifer thickness in matrix form (Figure 5). These values were then subtracted from the constant elevation of 730 feet. The results represent the bottom elevation of the aquifer. The aquifer is shown in a 3-D image in Figure 6.

Layer 2

The bedrock layer has a variable thickness, but because only about 10 feet of the bedrock contributes to the ground-water movement it was ideal to portray the bedrock as a single unit, 10 feet thick. Because there is no space in between layer 1 and 2, the top elevation of the bedrock was used as the bottom elevation of the aquifer. The bottom layer of the bedrock was calculated by subtracting 10 feet from the top elevations of the bedrock.

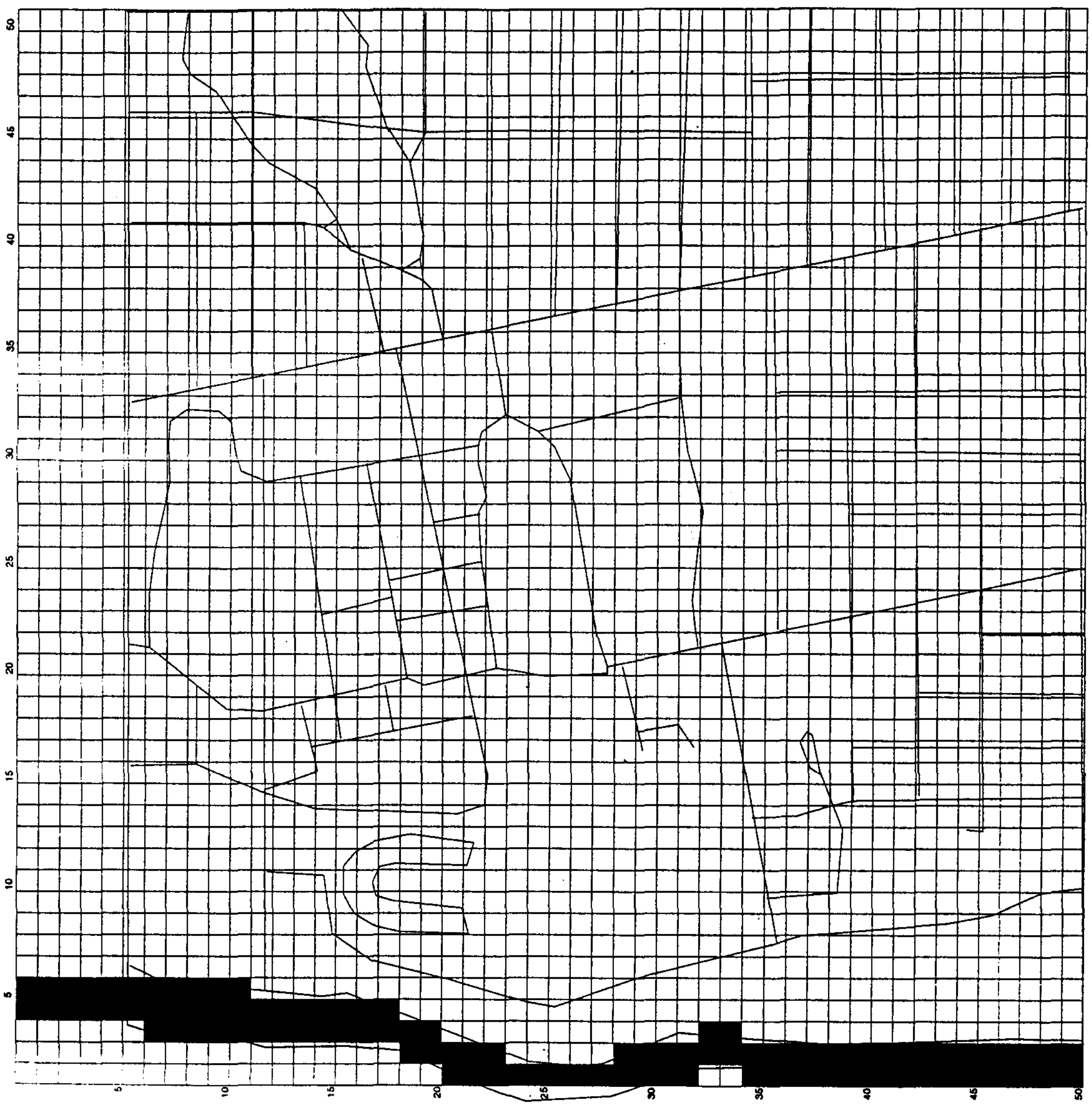

Figure 4 **Campus map on grid**

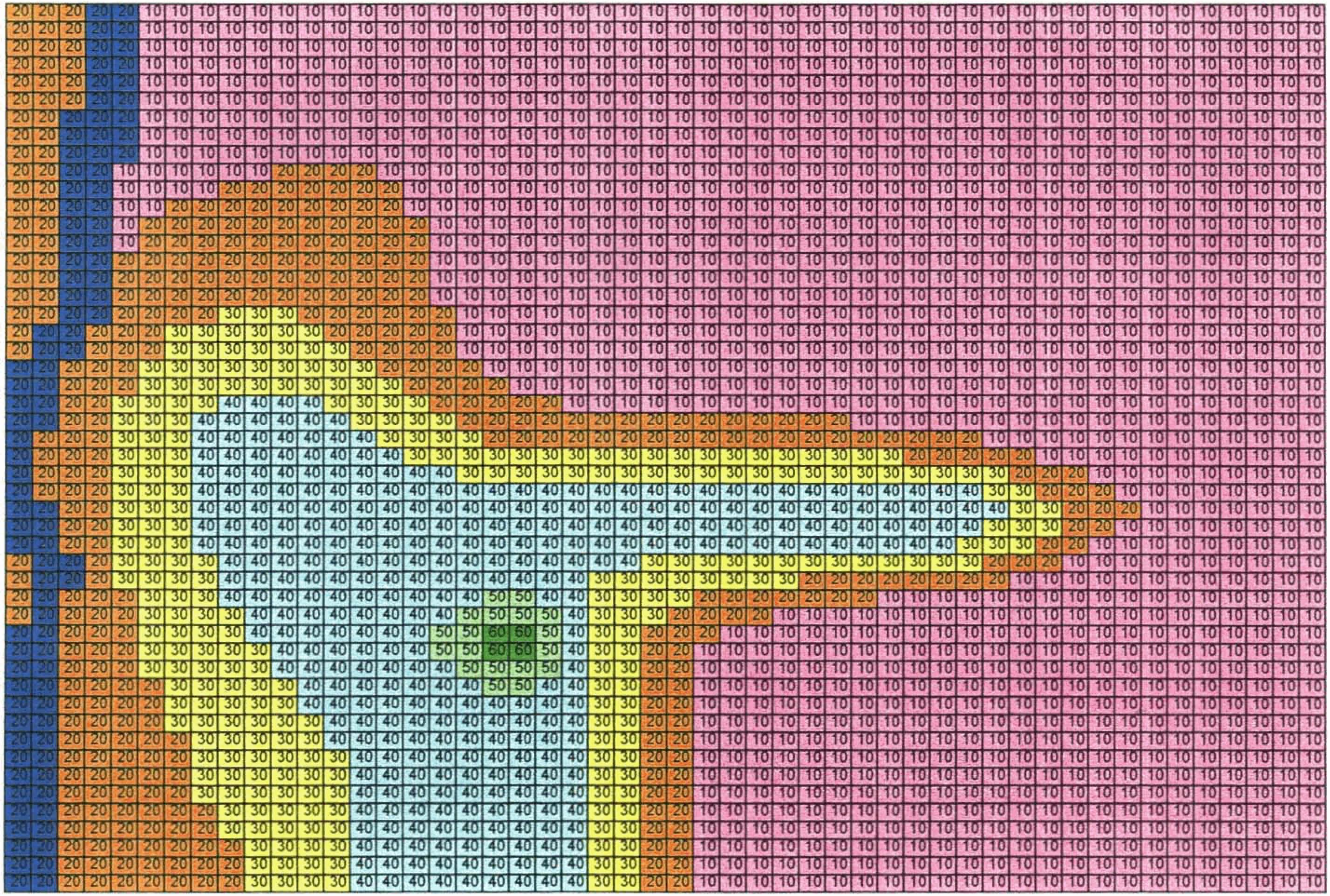

Figure 5 Excel spreadsheet of aquifer thickness

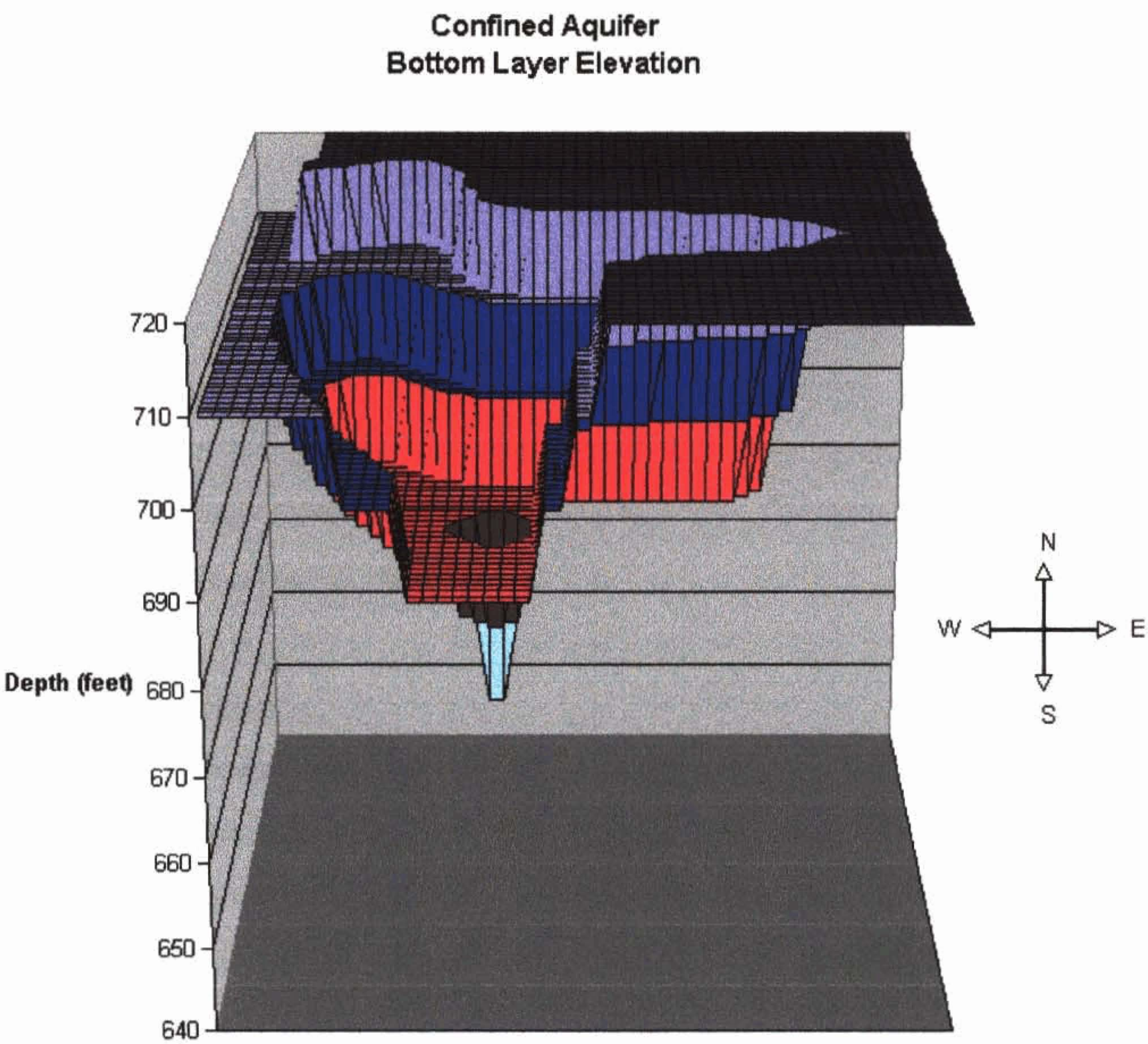

Figure 6 3-D Image of Aquifer

Four different spreadsheets were used with the help of Excel for top and bottom elevations of Layer 1 and 2. This information was then imported into MODFLOW.

Hydraulic Parameters

MODFLOW requires estimates of transmissivity and recharge rates in order to complete a steady-state simulation. To estimate transmissivity, the unit thicknesses from above were multiplied by a single hydraulic conductivity value. For layer 1 a hydraulic conductivity value of 300 ft/day was used, based on the data of Cunningham et al., (1996). For layer 2 a hydraulic conductivity value of 10 ft/day was applied.

Recharge rate was used as a calibration parameter. I started with approximately the same values as those reported by Cunningham et al., (1996). This report estimated recharge to be around 9.6×10^{-4} ft/day

Boundary Conditions

A requirement for all MODFLOW is a set of specified boundary conditions for all sides of the simulation domain. The Olentangy River is assigned a head of 720 feet. This value was chosen because on the topographic map the Olentangy River crosses the 720 feet contour line. The remaining side and bottom boundaries are considered as hypothetical no flow boundaries which is accomplished by default in the model. The top boundary is considered to be a recharge boundary.

Calibrations

The goal of calibrating is to replicate head values collected from the field using the model. This step can be achieved by one of two methods, trial and error or automated calibration. Trial and error is the preferred method in this case. Calibration is essentially a solution of the inverse problem. Unlike forward problems where data is given and an answer is calculated, inverse problems have a known solution and parameters are adjusted to achieve the desired results (Anderson et al. 1992).

In the area of interest, data were available for only a single well. A target point was placed where the well is located to calibrate the MODFLOW model. Recharge was adjusted in a series of runs until the 725-foot head value ran through the location of the target point. The resulting recharge value used was 2.5×10^{-3} ft/day. The calibrated model is shown in Figure 7.

Usually calibration requires a substantial number of data points. Due to the lack of hydraulic head data, this model can be considered poorly calibrated. The one value available does give some form of calibration to the model, but more data values would give more accurate calibration results. As a result, this model is calibrated to the best of my ability under the circumstances of few data.

Model Applications

The problem that The Ohio State University faces is that the Stadium is extremely close to the river and connected to the aquifer under The Ohio State Campus and the Olentangy River. I used the model to evaluate this problem in more detail. First I examined how lowering the field without inflow controls might affect the stadium. This

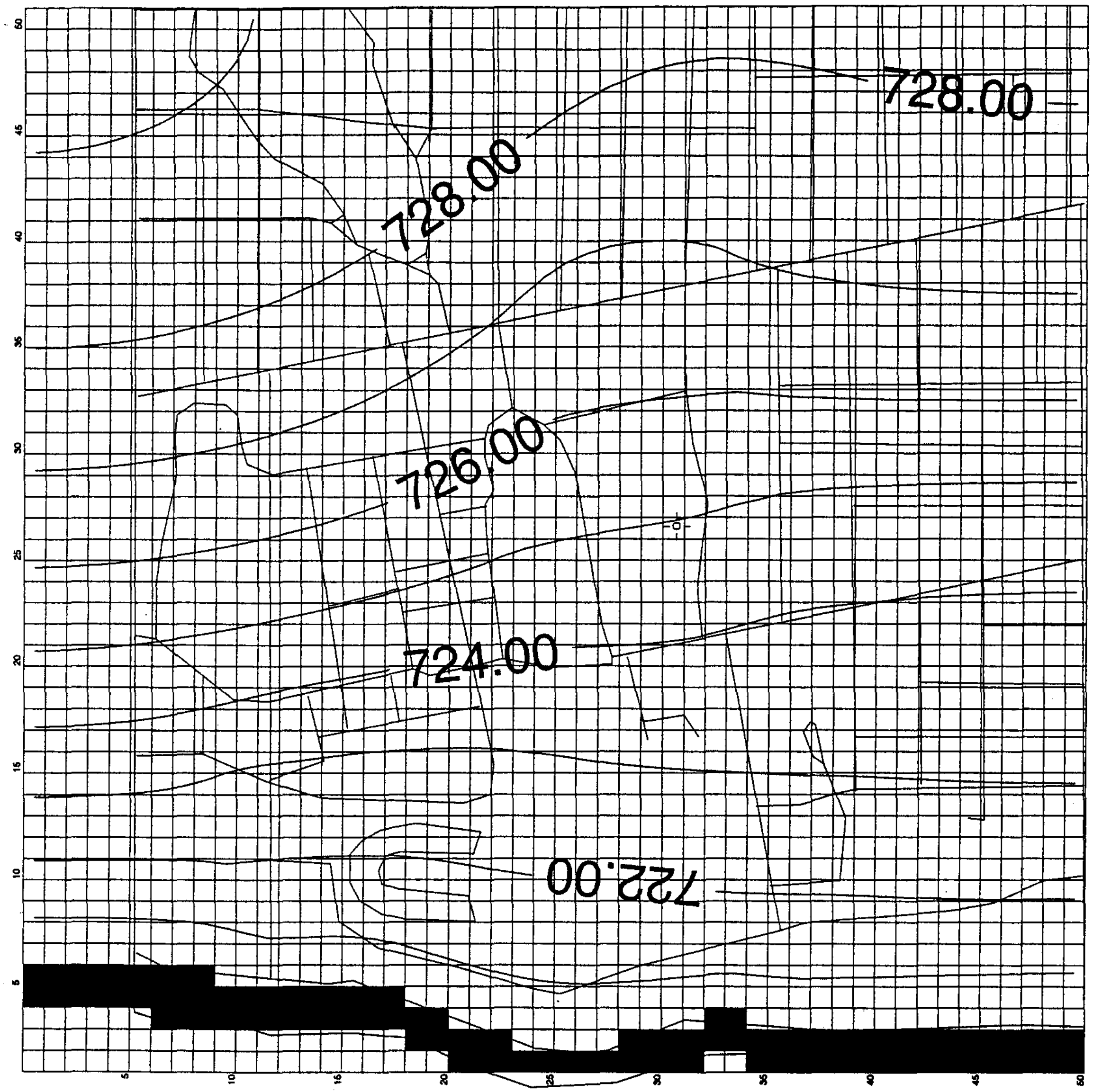

Figure 7 Calibrated model

effect was included in the model by adding constant head nodes of 715 feet above sea level corresponding to the location of the stadium. Figure 8 shows the resulting pattern of flow. As is evident, water from the upland area of campus, the river, and the flood plain north and south of the stadium flow toward the stadium. According to MODFLOW a total of 36275 ft^3/day is being pumped from the stadium to maintain a water level below the field.

To avoid these large pumping rates, the University derived to build a concrete wall around the stadium to the bedrock. If this solution had worked perfectly, as envisioned, the wall would have kept all the water out of the stadium. No-flow cells were added to the model to create a hypothetical simulation (Figure 9).

After the wall was build it was discovered that the bedrock allowed water to flow into the stadium threw fractured cracks on the bedrock surface. As a result the wall did not keep all the water out. To illustrate this simulation a hydraulic conductivity value of zero was added around the stadium, while the bedrock still had a value of 10 ft/day. The results are shown in Figure 10.

DISCUSSION

Mass Balance

A major indicator that a model is or is not working correctly is the results shown from the mass balance. Mass balance is the ratio of inflow to outflow. In a correctly working model the mass balance must be equal to or closely equal to zero. A perfect model that has a mass balance of zero indicates that the inflow is equal to the outflow. The results of mass balance for each model are shown in Table 1. The mass balances of

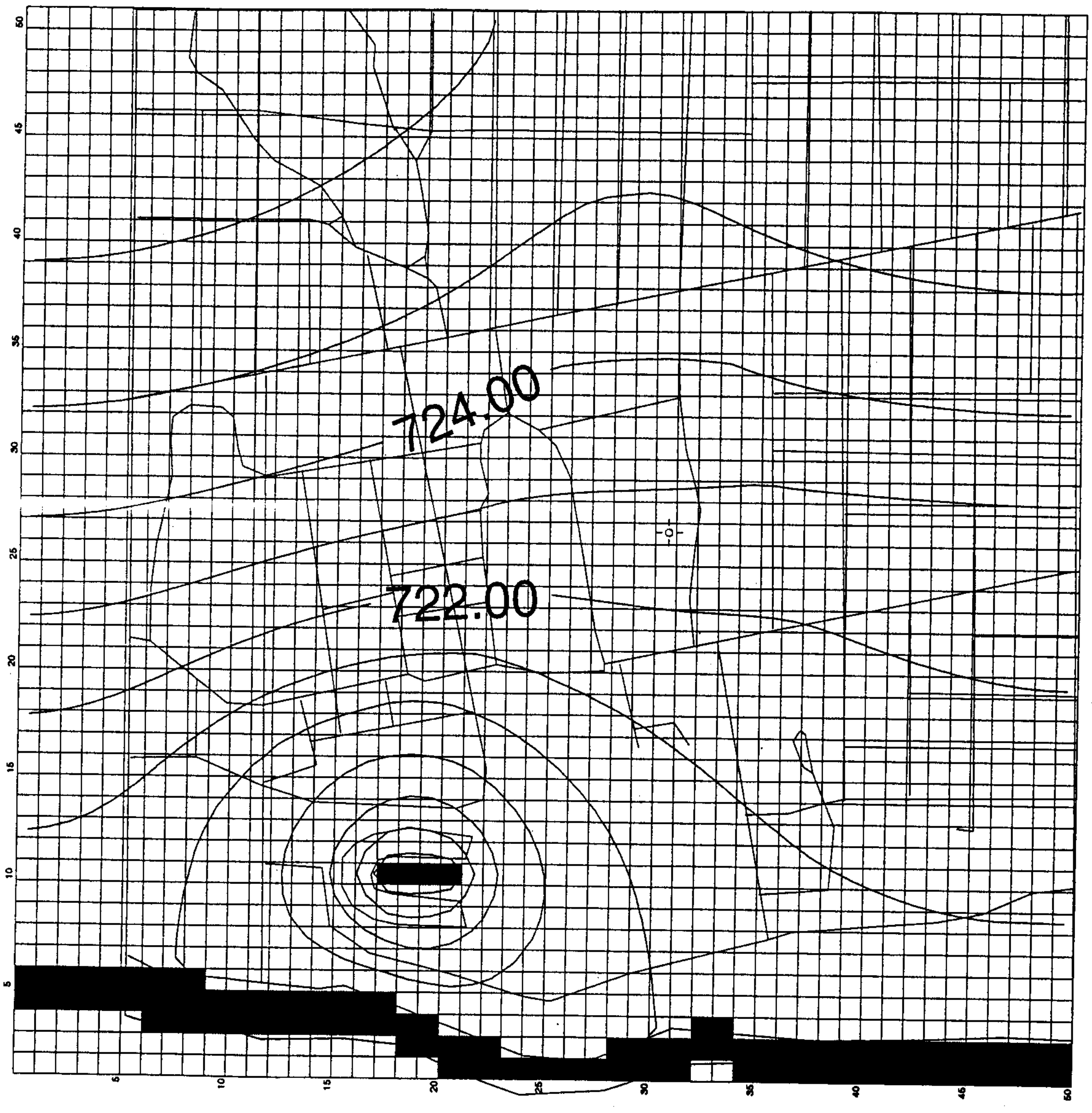

Figure 8 **Constant heads placed in the stadium to represent the lowering of the field.**

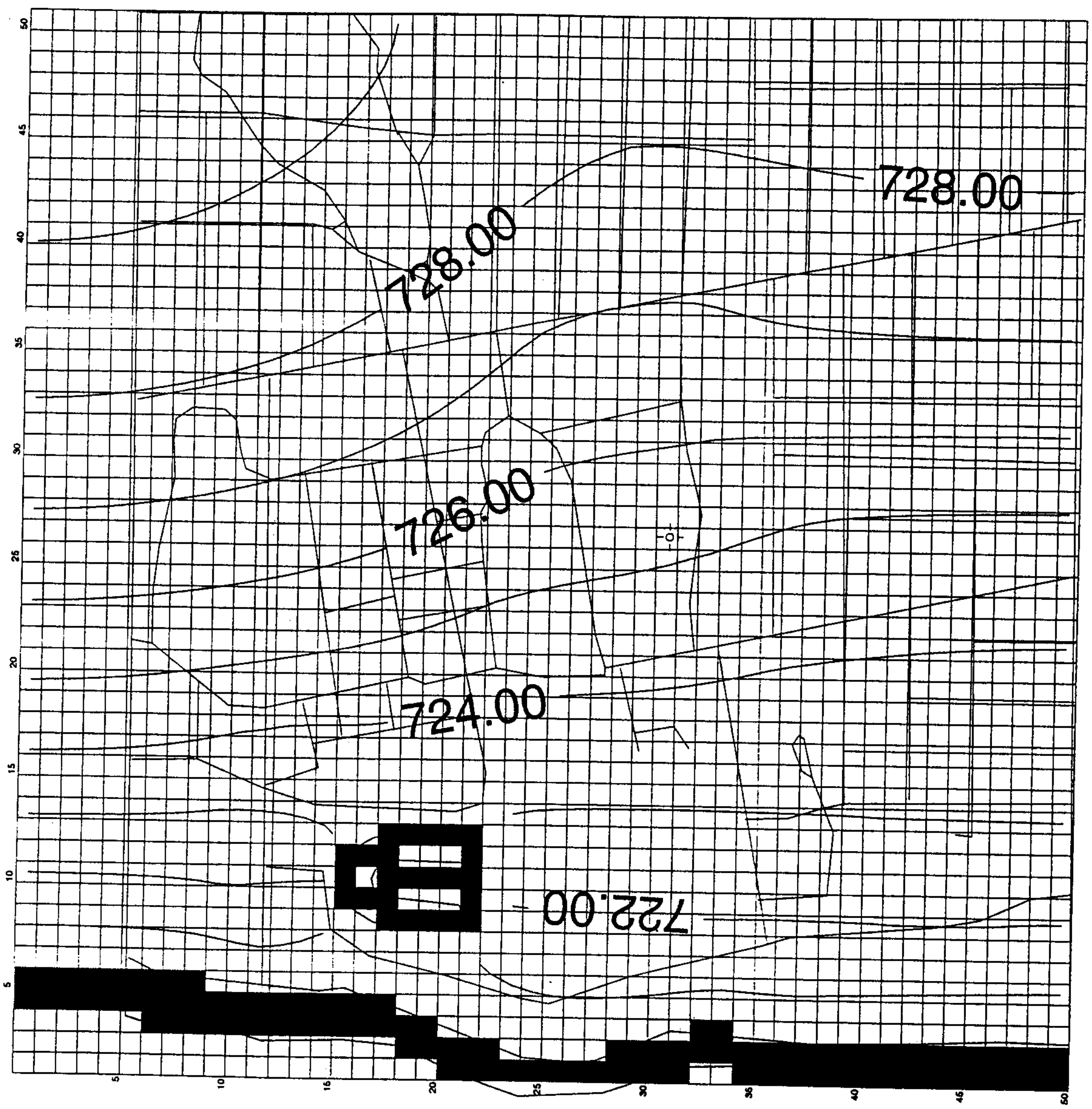

Figure 9 Hypothetical Model – Wall produces No-flow into stadium.

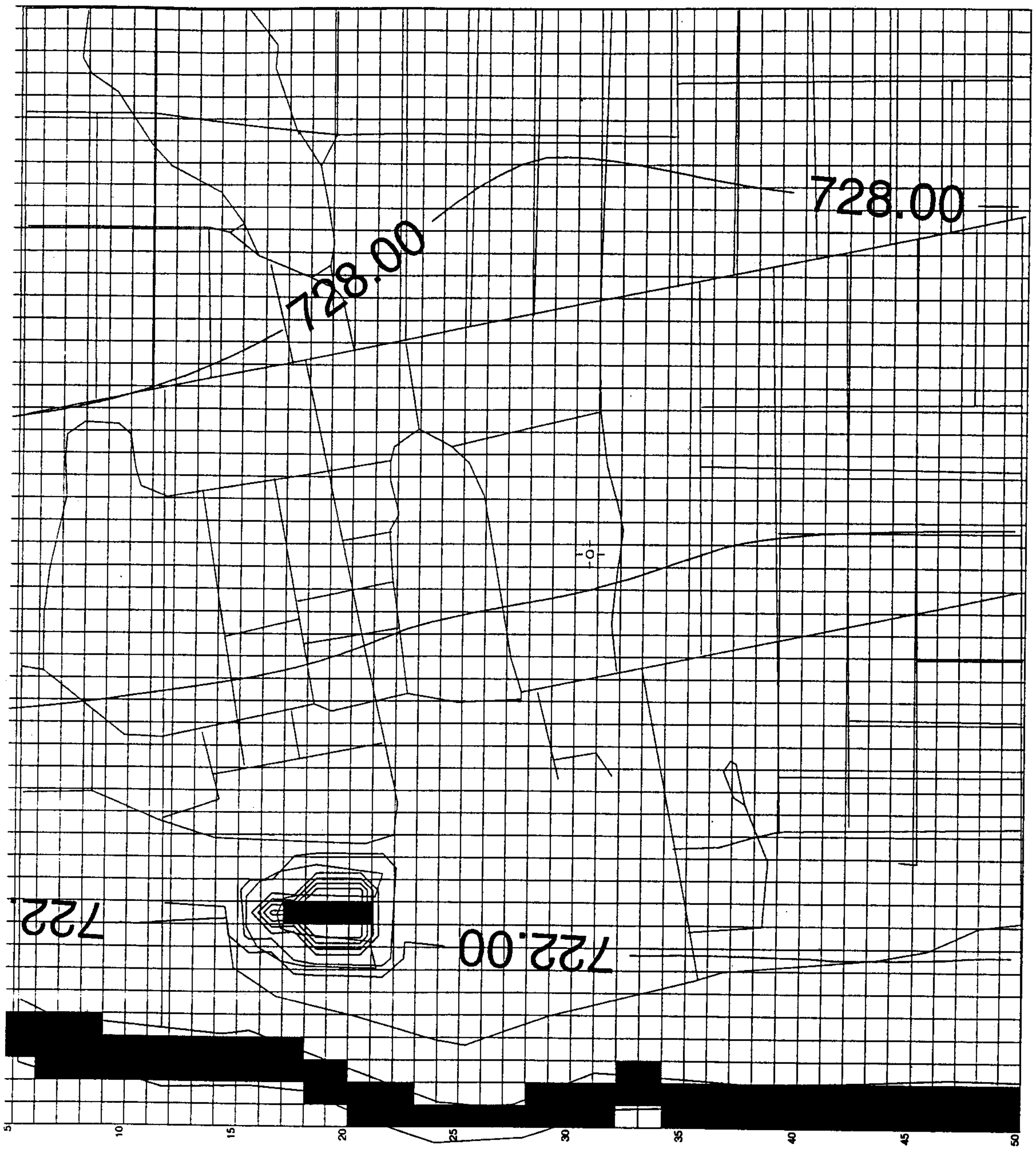

Figure 10 Wall around stadium with fractured bedrock.

Table 1. Mass Balance

Calibrated Model

	Inflows	Outflows
Bottom	1537.74 ft^3/day	1519.85 ft^3/day
Constant Heads	0 ft^3/day	100669.62 ft^3/day
Recharge	100266.69 ft^3/day	0 ft^3/day
Total	**101804.43 ft^3/day**	**102189.47 ft^3/day**

Percent Error: -0.378

Model representing lowering of the stadium field

	Inflows	Outflows
Constant Heads	36275.52 ft^3/day	136525.54 ft^3/day
Recharge	100099.71 ft^3/day	0 ft^3/day
Total	**136375.23 ft^3/day**	**136525.54 ft^3/day**

Percent Error: -0.110

Hypothetical Model – Wall produces no flow into stadium

	Inflows	Outflows
Bottom	1544.66 ft^3/day	1539.35 ft^3/day
Constant Heads	0 ft^3/day	99424.29 ft^3/day
Recharge	99264.85 ft^3/day	0 ft^3/day
Total	**100809.51 ft^3/day**	**100963.64 ft^3/day**

Percent Error: -0.153

Wall around Stadium with fractured bedrock

	Inflows	Outflows
Constant Heads	0 ft^3/day	101203.04 ft^3/day
Recharge	100099.71 ft^3/day	0 ft^3/day
Total	**100099.71 ft^3/day**	**101203.05 ft^3/day**

Percent Error: -1.10

all the simulations have a percent error of 1.1 or less. This result is relatively low and is a reasonable percent error, which indicates the models are working properly. As a result the models developed can be accepted.

Interpretation of the models

The model developed to represent the lowering of the stadium shows interesting results. Figure 8 shows a wide cone of depression that has formed around the stadium. This reveals that all the water from the upland area and also water from the Olentangy River are entering the stadium. This result would be likely because the stadium field is the lowest local discharge area point. Water has a natural tendency to flow from points of high to low head and thus, all the water entering the stadium from it's surroundings would be nothing less than expected.

The intended result of the wall built around the stadium was to keep all the water out. The model illustrated in Figure 9 shows this ideal situation, but as later is discovered to be nonrealistic. Comparing Figure 8 and 9 it is easily recognized that there are no longer any cones of depression around the stadium, which reveals water is no longer entering the stadium. The water rather goes around the stadium.

The most representative model for the current known situation of the stadium is shown in Figure 10. Although there are evident cones of depression present, they are not as widely spaced as in Figure 9. This indicates that water is still entering the stadium, but not as large of quantities as in the model represented in Figure 8.

CONCLUSION

The results produced from this MODFLOW model are concluded to be reasonable and acceptable. The mass balance is reasonable for each model because each have a percent error of 1.1 or less. The models provided me with unique insight into the dynamics of the ground-water movement of The Ohio State Campus. Although this study produced reasonable results, modifications can still be made to the each model. One such modification would be to gather more field data for calibrating the model. Along with more time to complete this study, the models developed can be made more complex to represent the ground-water movement in more detail.

ACKNOWLEDGMENTS

I would like to sincerely thank Dr. Franklin W. Schwartz for advising me during the development of this Senior Thesis. His patience and supervision to explain the world of ground-water movement has developed my interest and respect for the study and application of Hydrogeology.

References

Anderson, P. M., and W. W. Woessner. 1992. Applied Groundwater Modeling. Simulation of Flow and Advective Transport. Academic Press, San Diego.

Cunningham, W. L., E. S. Bair, and W. P. Yost. 1996. Hydrogeology and Simulation of Ground-Water Flow at the South Well Field, Columbus, Ohio: U.S. Department of the Interior, U.S. Geological Survey, Water-Resources Investigations Report 95-4279.

Domenico, A. P., and F. W. Schwartz. 1998. Physical and Chemical Hydrogeology. 2nd ed. John Wiley & Sons, Inc., New York.

McMillian, T. D., 1999. Geology of The Ohio State University, Columbus Campus. Senior Thesis.

Nalley, G. M., and R. J. Haefner. 1999. Simulation of the Effects of Nearby Quarrying Operations on Ground-Water Flow at the South Well Field, Franklin County, Ohio: U.S. Department of the Interior, U.S. Geological Survey, Water-Resources Investigations Report 99-4136.

Schalk, C. W., 1996. Estimation of the Recharge areas Contributing Water to the South Well Field, Columbus, Ohio: U.S. Department of the Interior, U.S. Geological Survey, Water-Resources Investigations Report 96-4039.